Bright Lyman Break Galaxy Candidates in the Sloan Digital Sky Survey First Data Release

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ABSTRACT

We report the discovery of six compact, starburst galaxy candidates with redshifts $2.3 < z < 2.8$ and r-band magnitudes $19.8-20.5$ in the Quasar Catalog of the SDSS DR1. The SDSS spectra resemble the composite spectrum of Lyman Break Galaxies (LBGs) at $z \approx 3$ (albeit with some differences and broader spectral lines), but the objects are $4-5$ magnitudes brighter than an "L_*" LBG. These objects could be extremely luminous LBGs, normal LBGs amplified by gravitational lensing, or a rare class of BAL quasars. In the first case, star formation rates inferred from the UV continuum luminosities, with no correction for dust extinction, are $\sim 300-1000$ M$_\odot$ yr^{-1}, similar to those of ultraluminous infrared galaxies, but in these UV-bright objects the star formation is evidently not obscured by high dust column densities. The SDSS images show no evidence of multiple imaging or foreground lensing structures. The spectra have fairly broad absorption features and prominent high-ionization absorption but do not show high-ionization emission lines and do not resemble known BAL quasars. A rough estimate of the luminosity function of the objects is above a Schechter function extrapolation from LBGs at fainter magnitudes. Improved optical spectra and observations at X-ray, IR, and sub-mm wavelengths could help determine the nature of these remarkable objects.

Subject headings: galaxies: starburst — surveys

1.   INTRODUCTION

One of the most important recent developments in observational cosmology is the discovery of a large population of star-forming galaxies at $z \approx 3$ (e.g., Steidel et al. 1996;

Lowenthal et al. 1997). These so-called Lyman break galaxies (LBGs) can be identified by their characteristic colors in deep imaging surveys. Spectroscopic surveys of LBGs have transformed our understanding of the history of cosmic star formation (e.g., Madau et al. 1996; Steidel et al. 1999) and of galaxy clustering in the early universe (e.g., Adelberger et al. 2003). At $R_{\rm AB} \approx 24.5$, the surface density of LBGs is ~ 1 arcmin^{-2}, and the luminosity function is well described by a Schechter (1976) function with a characteristic luminosity corresponding to an R$_{AB}$ apparent magnitude $m_* = 24.54$ at $z \approx 3$ (Adelberger & Steidel 2000).

Most known LBGs have been discovered in deep images covering small areas of the sky. The survey by Steidel et al. (2003), for example, contains more than 2000 spectroscopically confirmed galaxies, but the 17 fields in the study cover only ~ 0.38 deg^2. The brightest galaxies in this survey have $R_{\rm AB} \approx 23$. The only substantially brighter object known, MS 1512-cB58 with $R_{\rm AB} \approx 20.4$, was discovered serendipitously by Yee et al. (1996) as part of the CNOC-1 redshift survey, and is now understood to be magnified by a factor ~ 30 as a result of gravitational lensing by a foreground galaxy cluster (Seitz et al. 1998). Detailed studies of the stellar populations and interstellar gas properties of LBGs rest either on this single object (e.g., Teplitz et al. 2000; Pettini et al. 2000) or on composite spectra constructed from many individual galaxies (Shapley et al. 2003). The limited area of existing LBG surveys also means that the very bright end of the LBG luminosity function is unconstrained.

The imaging survey of the Sloan Digital Sky Survey (SDSS, York et al. 2000) complements existing LBG imaging surveys by covering a much wider area to a brighter limiting magnitude. Furthermore, because the SDSS quasar selection algorithm (Richards et al. 2002) identifies unresolved sources with non-stellar colors, rather than just objects with expected quasar colors, it *also* selects the most luminous LBGs as quasar candidates and targets them for spectroscopy. In a search for quasars with anomalously low C IV emission, Bentz & Osmer (2003) found one example of an apparently luminous, $z \approx 2.5$ starburst candidate that had been classified as a quasar by the SDSS spectroscopic pipeline in the Early Data Release (EDR, Stoughton et al. 2002) Quasar Catalog (Schneider et al. 2002). In this *Letter*, we describe a detailed search through the SDSS First Data Release (DR1, Abazajian et al. 2003) and the discovery of five additional objects with similar properties. These objects have intriguing properties that necessitate a variety of additional observations, and, if confirmed as starbursts, they would provide the first constraints on the space density of extremely luminous (in rest-frame UV) star-forming galaxies at high redshifts.

2. SPECTRAL ANALYSIS

As described by Schneider et al. (2003), the SDSS DR1 Quasar Catalog covers ~ 1360 deg^2 of the sky and contains 16,713 objects with rest-frame absolute magnitudes $M_i < -22$ (for $h \equiv H_0/100$ km s^{-1} Mpc$^{-1} = 0.7$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and a power law (frequency) continuum index of $\alpha_Q = -0.5$), at least one emission line with a FWHM larger than 1000 km s^{-1}, and reliable redshifts. For this investigation, we searched the SDSS DR1 Quasar Catalog for high-z starburst galaxies that might have been classified as quasars, limiting the catalog to $z > 2.3$ in order to probe the high-z regime of traditional LBG surveys. Color cuts were then applied to the 1658 objects satisfying the redshift cut. Although the filter systems are different, those objects with optical colors satisfying

$$g - r \leq 1.2, \ u - g \geq g - r + 1 \tag{1}$$

are analogous to the objects that would be detected by the LBG color criteria of Shapley et al. (2003). A total of 591 objects met the color criteria, and they were all visually inspected for absorption line features similar to those in the LBG composite spectrum of Shapley et al. (2003), and for the absence of characteristic quasar emission lines from highly ionized species. Six objects (including the original object discovered in the EDR by Bentz & Osmer 2003) displayed these spectral signatures of a starburst galaxy. Table 1 lists the six candidate objects and their properties. Figure 1 shows the individual spectra of the six candidates taken with the $2.5-$m SDSS telescope alongside the composite spectrum of 811 galaxies obtained with the $10-$m Keck telescope by Shapley et al. (2003).

The six candidates are red relative to normal quasars, but because they have non-stellar colors and are unresolved at the resolution of SDSS imaging, they meet the SDSS selection criteria for high-redshift quasar candidates (Richards et al. 2002) and were targeted for spectroscopy. We checked the SDSS DR1 spectral database to confirm that there were no objects classified as galaxies with $z > 2.3$ and no high-z quasar candidates satisfying our selection criteria that might have been rejected from the Quasar Catalog because they failed to pass the 1000 km s^{-1} emission line cut.

Table 1 lists the redshifts and broad-band photometric properties of the six candidates, taken from the SDSS DR1 Quasar Catalog (Schneider et al. 2003). All six objects are 4-5 magnitudes brighter than an L_* LBG, and 2-3 magnitudes brighter than the brightest LBG detected by Steidel et al. (2003).

3. LENSED LBGS, ULTRALUMINOUS LBGS, OR BAL QUASARS?

From the absence of emission lines of highly ionized species, such as N V and C IV, it is obvious that these objects are not normal AGN. But are they normal LBGs that have been amplified by gravitational lensing, extremely luminous LBGs, or unusual broad absorption line (BAL) quasars?

The objects were found by searching for absorption and Lyα features similar to those of the LBG composite, so by definition they share many spectral similarities. There is strong evidence in most of the candidates for absorption from Si II λ1260, C II λ1334, Si IV $\lambda\lambda$ 1393,1402, C IV $\lambda\lambda$1548, 1550, and Al III $\lambda\lambda$1854, 1862. In a few of the candidates, there is even noticeable absorption from O I λ1302, Si II λ1304, Si II λ1526, Fe II λ1608, and Al II λ1670. The precedent of MS 1512-cB58 suggests that the high apparent brightness of these objects could be a consequence of lensing. We inspected the SDSS images of the six candidates for evidence of multiple images or possible foreground galaxies or clusters, but all of the systems are consistent with lone, unresolved point sources with unexceptional foreground environments. We also counted the numbers of objects classified as extended in the DR1 imaging catalog within a 5$'$ radius of five of the six objects,[1] and similarly for control fields offset by $1° - 4°$. The counts did not show any statistically significant excess of extended sources around the candidates, except possibly for SDSS J1444+0134. The SDSS data are not sufficient to rule out sub-arcsecond image splitting or the presence of foreground systems at likely lens redshifts of $z \sim 1$.

At present, the main evidence against the lensing hypothesis comes from the differences between the LBG composite spectrum and the spectra of the galaxy candidates. The candidates are redder than most LBGs, and most of their absorption features are broader, as are their Lyα profiles.[2] While we would not expect such differences if these were normal LBGs, they might arise if the objects have extremely high star formation rates (SFRs). If we assume that lensing and AGN contributions are unimportant, we can follow the standard practice of estimating SFRs from the continuum luminosity at λ1500 Å, which is produced mainly by young O and B stars. We estimate the rest-frame λ1500 Å flux directly from the calibrated spectra and convert to luminosity assuming a cosmological model with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$. Assuming a Salpeter IMF with mass limits of 0.1 to 100 M$_\odot$ and a

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[1]We were not able to carry out the counts for J1553+0056 because of a difficulty with the database.

[2]The FWHMs of the Lyα emission lines range from $\sim 1100 - 3000$ km s^{-1}. SDSS J1340+6344 and SDSS J1432-0001 have fairly symmetric Lyα profiles, while the LBG composite has a P-Cygni type asymmetry suggestive of outflows.

10^8 yr old continuous star formation model, Kennicutt (1998) derives the relation

$$\text{SFR } M_\odot \text{ yr}^{-1} = 1.4 \times 10^{-28} L_\nu(\lambda 1500) \tag{2}$$

between the star formation rate and the luminosity density L_ν (in ergs s^{-1} Hz^{-1}) at $\lambda =$ 1500Å. The implied SFRs are tabulated in Table 2, along with the measured flux in the observed frame at $\lambda 1500$ Å $\times(1 + z)$. As expected for objects as bright as these, the SFRs are very high, ranging from ~ 300 M$_\odot$ yr^{-1} to over 1000 M$_\odot$ yr^{-1}.

The values in Table 2 assume no dust extinction and are therefore lower limits to the "true" SFRs, at least if the assumed IMF is correct. Lyman break galaxies in typical spectroscopic surveys have similarly estimated SFRs in the range $\sim 50 - 100 h_{70}^{-2}$ M$_\odot$ yr^{-1} *after* correction for an average factor of ~ 7 attenuation by dust (Shapley et al. 2003). As previously mentioned, our candidates are redder than the LBGs in the Steidel et al. (2003) survey, which suggests that their extinction corrections should be larger, pushing the corrected SFRs to thousands of M$_\odot$ yr^{-1}. The stellar winds and interstellar turbulence associated with such extreme SFRs could account for the relatively broad absorption features and the strength of high excitation absorption seen in some of our candidates.

The brightest sub-mm galaxies are inferred to have comparable or, in some cases, even higher SFRs at these redshifts (see, e.g., Chapman et al. 2003), but in these objects most of the energy from massive young stars is absorbed and re-radiated by dust. The SCUBA source in N2 850.4 (Smail et al. 2003), with an estimated SFR ~ 300 M$_\odot$ yr^{-1}, has an optical spectrum reminiscent of those in Figure 1, though our objects do not show P-Cygni profiles. High-redshift galaxies with such SFRs *should* appear in the SDSS if they have moderate UV extinction, and our candidates could plausibly represent a later evolutionary stage of luminous sub-mm galaxies, with young stellar populations that have burned through enough of their dusty envelopes to become visible in the rest-frame UV.

Finally, there is the possibility that these luminous objects are powered by black hole accretion rather than star formation, and that they represent a very unusual class of BAL quasars. In favor of this interpretation, two of the spectra show evidence for broad C III] emission, and some have very broad absorption lines, up to ~ 7600 km s^{-1}. The strengths of the absorption features from highly ionized species are also much stronger than the low ionization absorption features. However, the candidates do not show typical BAL profiles, and we are not aware of any analogs of these objects among previously discovered BALs. There is significant variation among the spectra in Figure 1, and the relative importance of star formation and AGN activity could be different from object to object.

4. THE BRIGHT END OF THE LBG LUMINOSITY FUNCTION

If we assume that the ultraluminous LBG interpretation is correct, and that we can therefore ignore lensing amplification and AGN contributions, then we can constrain the bright end of the rest-frame UV luminosity function of high-redshift galaxies. Our estimate here is necessarily crude, (1) because we have only six objects, and (2) because assessing completeness as a function of luminosity and redshift would require detailed simulation of the SDSS quasar target selection algorithm. We make the conservative assumption that the selection efficiency is unity in the redshift range $2.3 < z < 2.8$ over the 1360 deg^2 area of DR1, for objects above the $i = 20.2$ apparent magnitude limit of the quasar catalog. Our objects lie within a 1-magnitude bin, with median redshift $z = 2.55$ and median absolute magnitude $M_{\rm UV} \approx -25.4$.[3] We estimate $\Phi(M) = \sum_{j=1}^{6} 1/V_{a,j} = 2.52 \times 10^{-9} h^3$ Mpc^{-3} mag^{-1}, where $V_{a,j}$ is the comoving accessible volume for galaxy j, which we take to run from $z = 2.3$ to the smaller of $z = 2.8$ and $z_{\rm max}$, the redshift at which the galaxy's apparent magnitude would hit the $i = 20.2$ limit. The $z = 2.8$ upper limit is based on the maximum redshift of our candidates, and while the selection function may continue beyond this redshift, it is likely to decline as Lyα moves past the peak of the g-filter. If we assumed instead that each galaxy could be seen all the way to $z_{\rm max}$, then our density estimate would drop by 20%.

Figure 2 shows this estimate in the context of the LBG luminosity function estimated by Adelberger & Steidel (2000) from a combination of ground-based data and the Hubble Deep Field. Circles show the Adelberger & Steidel (2000) data points, with no correction for dust extinction, and the solid line shows their Schechter function fit. The open triangle shows our above estimate at $z = 2.55$, with an error bar that corresponds to the Poisson error on six objects. We plot our point at the median apparent magnitude $r \approx 20.3$, ignoring the difference between the Sloan r-band and Adelberger & Steidel's R-band. Our assumption of unit selection efficiency is probably too generous, so the most likely value for the space density is above the data point. Since the Adelberger & Steidel (2000) data are given in terms of apparent magnitude and their galaxies have a median $z \approx 3$, we also plot a filled triangle that shows the effect of moving our galaxies from $z = 2.55$ to $z = 3$, using a K-correction based on the median spectral slope of $\alpha = -2.16$, with $f_\nu \propto \nu^\alpha$, derived by fitting the $griz$ magnitudes.

Our estimate of the luminosity function at $r \approx 20.3$ is above the Schechter function extrapolation from fainter magnitudes. However, there is no reason to expect that the high-redshift, rest-frame UV luminosity function should be described by a Schechter function over

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[3] We calculate the absolute magnitude from the i-band apparent magnitude, so it corresponds to rest-frame wavelength $7600\text{Å}/(1+z) \approx 2100\text{Å}$.

such a wide range in luminosity, especially given the importance of recent star formation history and the geometry of extinction in determining a galaxy's luminosity at $\lambda 1500$Å. A power law connecting our data point (offset to $z = 3$) to the brightest data point from Adelberger & Steidel (2000) has a slope of $R_{\mathrm{AB}}^{-1.93}$ (or $L^{-2.93}$).

A variety of follow-up observations could help to determine the nature of these remarkable objects. High-resolution imaging to search for image splitting and deeper imaging to search for foreground structures could test the lensing hypothesis. Better optical spectra would allow better measurements of absorption profiles and tighter constraints on broad emission lines, and they might reveal high-excitation photospheric lines that would be the signature of starburst activity. Near-IR spectroscopy, sub-mm imaging, and X-ray measurements could better quantify the importance of dust extinction and AGN activity. If these objects are confirmed as extreme LBGs, they demonstrate that the stupendous starbursts so often veiled by thick layers of dust can sometimes emerge to show their true colors.

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Table 1.   Properties of Starburst Candidates

| Object | z^{a} | Colors and Magnitudes[a] | | | | | | |
		u−g	g−r	r−i	i−z	r Obs.	i Obs.	i Abs.[b]
SDSS J024343.77−082109.9	2.59	2.181	0.390	0.319	0.500	20.403	20.084	-25.916
SDSS J114756.00−025023.5[c]	2.56	3.629	1.170	0.532	0.679	19.825	19.293	-26.678
SDSS J134026.44+634433.2	2.79	2.453	0.689	0.465	0.340	19.823	19.358	-26.792
SDSS J143223.10−000116.4[d]	2.47	1.885	0.615	0.399	0.609	20.514	20.115	-25.810
SDSS J144424.55+013457.0	2.66	2.405	0.622	0.433	0.349	20.510	20.077	-26.028
SDSS J155359.96+005641.3	2.63	2.719	0.562	0.523	0.447	20.199	19.676	-26.524

[a]Values taken from Schneider et al. (2003).

[b]As determined by Schneider et al. (2003), with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$; note that this absolute magnitude is extrapolated to rest-frame i-band assuming $\alpha_Q = -0.5$, while our objects are much redder.

[c]SDSS J114756.00−025023.5 is also a 2MASS object (Cutri et al. 2003).

[d]SDSS J143223.10−000116.4 is also an EDR object (Schneider et al. 2002; Bentz & Osmer 2003).

Table 2.   Star Formation Rates

Object	$F_\lambda(\lambda 1500 \times (1+z))^{\mathrm{a}}$ $(10^{-17}$ erg s^{-1} cm^{-2} Å$^{-1})$	SFR[b] $(M_\odot$ yr$^{-1})$
SDSS J0243−0821	2.7	550
SDSS J1147−0250	2.7	530
SDSS J1340+6344	4.1	1100
SDSS J1432−0001	1.8	320
SDSS J1444+0134	3.7	820
SDSS J1553+0056	2.6	560

[a]Flux in observed frame at $\lambda = 1500 \times (1+z)$, with a characteristic uncertainty of 0.3×10^{-17} erg s^{-1} cm^{-2} Å^{-1}

[b]Assumes a Salpeter IMF with mass limits between 0.1 and 100 M$_\odot$ and a 10^8 year old continuous star formation model (Kennicutt 1998). No corrections for dust have been applied.
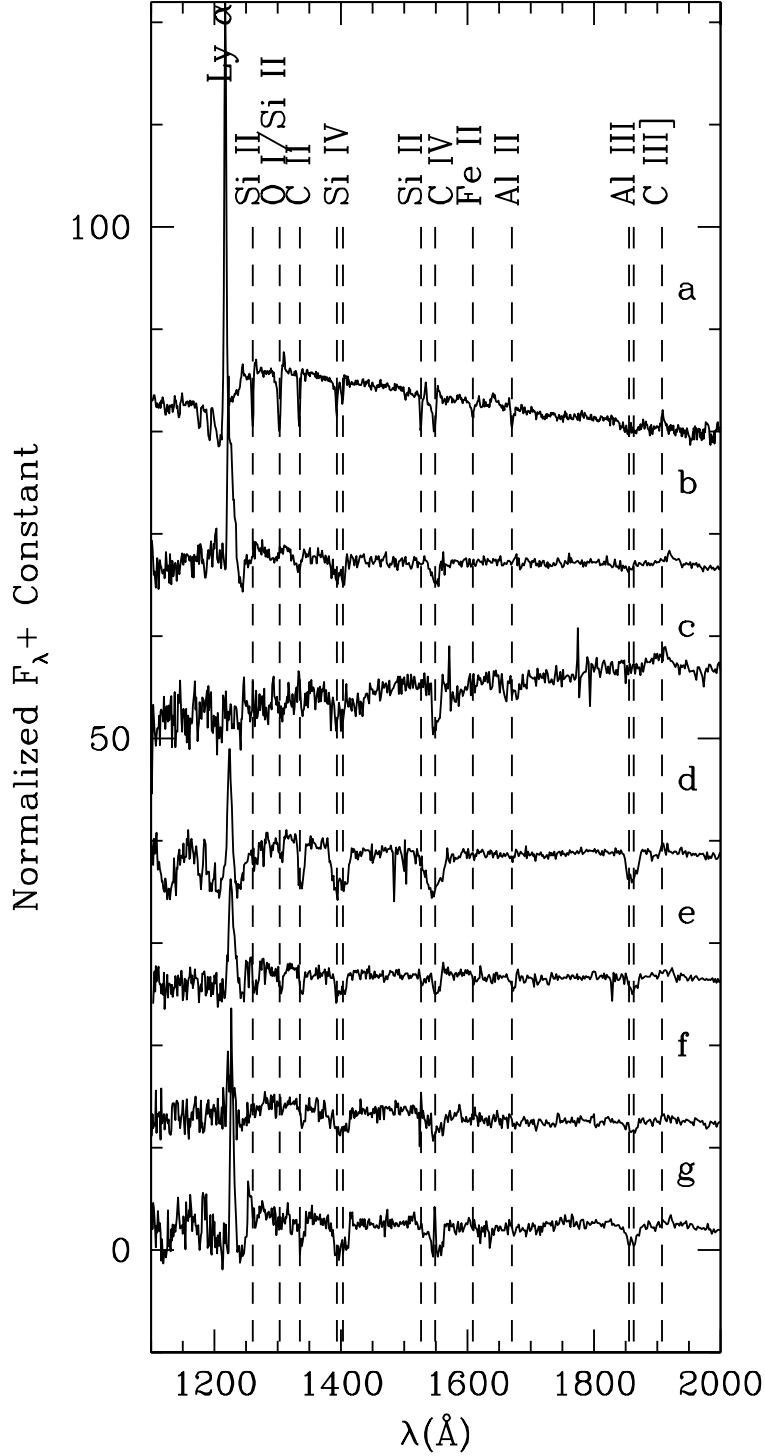
Fig. 1.— Rest frame spectra of the Lyman break composite (Fig. 1a, Shapley et al. 2003) and the six candidate starburst galaxies. The Sloan spectra have been smoothed over five pixels and are as follows: b.) SDSS J0243-0821, c.) SDSS J1147-0250, d.) SDSS J1340+6344, e.) SDSS J1432-0001, f.) SDSS J1444+0134, and g.) SDSS J1553+0056
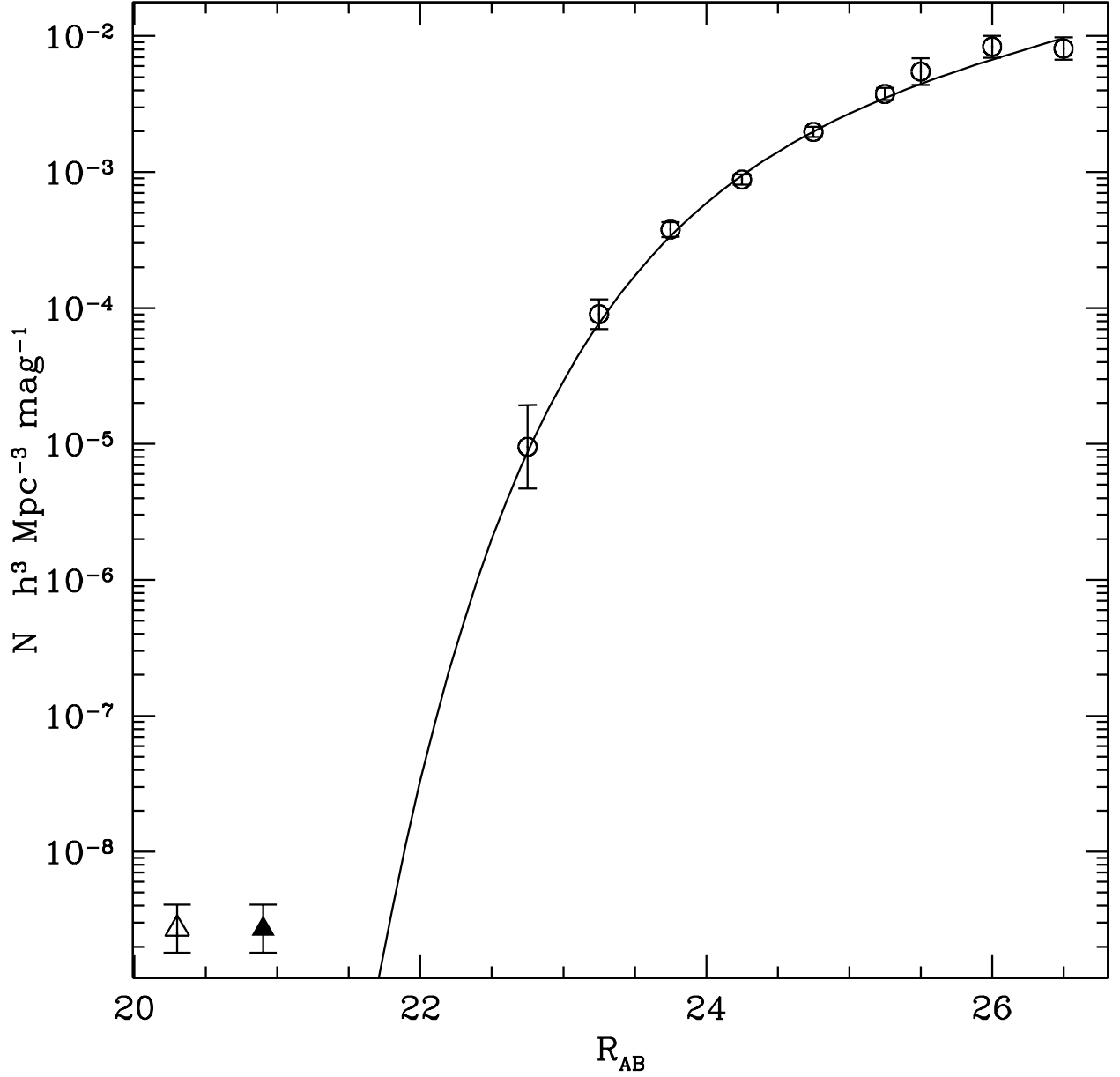
Fig. 2.— Luminosity function of starburst galaxies at redshifts $z \approx 3$ (for $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). The circles are data points from Adelberger & Steidel (2000), and the solid curve shows their Schechter function fit with parameters $\Phi_* = 4.4 \times 10^{-3} h^3$ Mpc^{-3} mag^{-1}, $m_* = 24.54$, $\alpha = -1.57$. The open triangle is the additional data point based on the objects described in this work, with errorbars showing the Poisson noise for six objects. The filled triangle shows the effect of changing from $z = 2.55$, the center of our redshift bin, to $z = 3$, the typical redshift of the Adelberger & Steidel (2000) objects.